

ROCKET LAUNCH TRAJECTORY SIMULATION MECHANISM

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Abstract

The design and development of a Trajectory Simulation Mechanism (TSM) for the Launch Systems Testbed (LST) is outlined. In addition to being one-of-a-kind facility in the world, TSM serves as a platform to study the interaction of rocket launch-induced environments and subsequent dynamic effects on the equipment and structures in the close vicinity of the launch pad. For the first time, researchers and academicians alike will be able to perform tests in a laboratory environment and assess the impact of vibroacoustic behavior of structures in a moving rocket scenario on ground equipment, launch vehicle, and its valuable payload or spacecraft.

INTRODUCTION

A successful space mission requires thorough consideration of sound and vibration effects. Historical data [1-3], analytical predictions [4,5], ground acoustic and vibration tests on scaled and full-scale models [3], engineering judgment [5,6], and test-analysis correlation [7-10] are all used in the design cycle phases of the launch vehicle, spacecraft, and the launch pad. Cost considerations have placed significant emphasis on the use of analytical methods

and test techniques that lead to overdesign. Examples of the results of cost reduction efforts are force-limited vibration, uniform test standards, payload fill factors, and more accurate sound and vibration analytical predictions.

Background

There are a number of critical structures (e.g., bridges, offshore platforms, aircraft, rocket engines, and launch pad structures) for which structural integrity is of the utmost importance. Architects and designers must consider the effect of random dynamic loads (e.g., earthquakes, water waves, aerodynamic loads, or acoustic pressures) in the design cycle. Since the discussion of this paper is limited to launch pad structures accurate characterization of acoustic pressure loads (Figure 1) is paramount to the understanding of structural dynamic behavior [1].

The design of launch pad structures, particularly those having a large area-to-mass ratio, is governed by launch-induced acoustic pressures, which are long-duration (< 20 seconds) dynamic activities, exhibiting nonstationary random behavior. The factors influencing acoustic excitation or forcing on any pad structure are numerous (rocket thrust, acoustic efficiency, supersonic mixing of exhaust plumes from clustered engines, launch trajectory, ground reflections, atmospheric conditions, sound directivity patterns, types of deflectors, exposure duration, vibroacoustic coupling, etc.). Moreover, the pad placement, shielding, material and geometrical attributes, mounting, and operational aspects of pad structures also influence their dynamic behavior. Thus, it is impossible to include the above factors in any comprehensive and accurate analytical treatment.

Because of the unique nature of launch environment, there is incomplete knowledge within the aerospace industry or the Government on the prediction of structural response to launch-induced acoustic environment. The problem is especially acute for new launch systems that have never been launched but require the design of reusable and survivable launch facilities with launch environment-mitigating features like sound suppression water and innovative exhaust ducts. Acoustic impact must be incorporated early in the design cycle and definitely prior to fabrication and installation. However, significant cost overruns have meant that seldom are all components fully and accurately qualified prior to launch.

Over the last several decades, NASA's John F. Kennedy Space Center (KSC) has led the way in the development of field-measurement-based analytical tools for accurate prediction of rocket launch-induced noise and subsequent dynamic response of structures [6-9]. This is especially important since full-scale acoustic and vibration testing of launch vehicles, spacecraft, and launch pad is often difficult and measurement of vibration on launch pad structures is often cost prohibitive. Space Shuttle launches provide a unique platform to integrate dynamic acoustic tests in the structural design analysis process, not possible in the laboratory [10].

LAUNCH SYSTEMS TESTBED

NASA has designated KSC as the Center for Excellence for launch and payload processing systems. Under this mandate, KSC is required to address four important goals: (1) ensure sound, safe, and efficient vibroacoustic techniques are in place for private/commercial processing; (2) increase the operational knowledge in the design/development of payloads and new vehicles; (3) partner to develop new technologies for future space initiatives; and (4) continually increase core capabilities to meet varying customer needs and demands.

The newly implemented LST is an avenue through which KSC will accomplish the above goals. LST's overall mission is to reduce costs and increase safety, reliability, and availability of launch structures and mechanisms exposed to rocket launch environments. Brief aspects of design and infrastructure development of the Rocket Launch Trajectory Simulation Mechanism (TSM), key LST components, are the focus of this paper.

LST projects will focus on the following technical areas:

- Predict, measure, and validate acoustic excitation models
- Enhance structural vibration response methods
- Develop and evaluate acoustic suppression systems
- Analyze exhaust plume using computational fluid dynamics
- Optimize exhaust duct configurations for new vehicles
- Institute rocket noise and vibration scaling methodologies

The current LST capabilities include:

- Specialized personnel with acoustics, structural dynamics, test, launch environment data analysis, and computational fluid dynamics experience
- A unique launch environment (acoustics, vibration, strain, etc.) database for over 100 launches (serving as a knowledge reservoir)
- Launch environments prediction and structural analysis methodologies to assess nonstationary random data
- A unique, small-scale rocket liftoff test facility to simulate moving rocket scenarios required in the real world

One key objective of LST is to simulate small-scale launch environments for use in testing and evaluation of launch pad designs for future space vehicles for NASA. The end result is to arrive at launch-induced acoustic excitation models that yield more realistic structural vibration response estimates than those provided by the methods currently available.

TRAJECTORY SIMULATION MECHANISM

At KSC, significant effort was undertaken to measure acoustic loads and vibration response under the Verification Test Article (VETA) project. VETA proved to be a structural dynamist's dream come true. The premise behind VETA testing [10] was if acoustic loads cannot be generated in the lab; take the entire testing operation to the field (Figure 2). This totally

eliminated the ambiguity of simulating the launch environment. Despite this, VETA series of tests paved the way for validating the vibration response methodology developed over a decade at KSC [7-9].

As outlined earlier, launch-induced acoustic excitation is a nonstationary and random and exhibits non-Gaussian behavior. Unlike vehicles and payloads, launch support structures cannot be tested and verified prior to launch. Fully valid acoustic loads can only be generated by the launch of a full-scale vehicle in the strictest sense. Laboratory acoustic tests come close to applying very high acoustic loads. However, these lack the true simulation of the dynamic nature of the launch environment. Even a limited simulation of nonstationary random environment displaying characteristics of true acoustics has been lacking to date.

A survey of the literature on small-scale testing of rockets did not reveal any past effort to simulate a test facility that could handle a moving rocket scenario to assess the impact of launch-induced environments on ground equipment and structures within the vicinity of the launch pad. Most studies have relied on static firing of scaled or full-scale engines. Some of the early tests included horizontal firings, yet some other researchers have attempted to take acoustic data by moving the rocket nozzle vertically or horizontally in a stepwise manner. These static or quasi-static tests do not simulate the launch environment in a true sense.

Lessons learned from literature survey, enhancements to other test facilities, and the experience from VETA were carefully incorporated in the development stage of TSM. One drawback of VETA testing was the time factor. To collect statistically significant data necessitated years of testing. Design and development of TSM capability addressed the problem of acquiring acoustical and vibration data from multiple launches in a short time. Moreover, the TSM is used to generate a nonstationary, scaled acoustic load. Our primary goal in the design and development of the TSM was to eliminate the most important drawback – the ability to simulate the launch trajectory in a dynamic sense, hitherto not attempted by researchers. Thus, it was planned to design and construct a test facility that is capable of being configured to scaled launch environments of future vehicles. The scaled launch environments will be used to predict the full-scale launch environments.

Performance Parameters

TSM is a one-of-a-kind, scaled, moving, single/multiple, combustive, and noncombustive supersonic jet plume test and research laboratory. TSM is capable of simulating varied launch trajectories while inducing nonstationary random acoustic loads on pad structures similar to those generated by the launch of a rocket. LST projects will focus on vibroacoustics, acoustic suppression systems exhaust plume flow modeling, exhaust duct optimization, scaling methods, assessment of composite structures, fatigue life prediction, hydrogen entrapment, and related areas.

Table 1 outlines the general requirements that were developed prior to the design of TSM. The overall project plan, encompassing cold jet tests followed by hot and combustive

jets, primarily drove the requirements. Issues pertaining to the use of liquid and solid fuels and their impact on the TSM were considered. Based on these needs, the operable life of TSM was determined to be around 10 years. This is alleviated by TSM's usage rate of 1500 rocket launches per year, compared to the Space Shuttle's rate of 7 to 8 launches per year.

The design and development of TSM capabilities were largely based on U.S. launch industry requirements. Table 2 documents performance requirements of the TSM. The Space Shuttle will most likely be the mainstay of NASA's avenue for the immediate future. The International Space Station (ISS) goals and objectives drive this use. Therefore, it was decided to scale vertical and horizontal travel based on the Space Shuttle launch scenario. In addition, requirements for TSM vertical speeds and horizontal speeds were driven by Space Shuttle trajectory. The travel speeds can be precisely controlled in fractional increments. Thus, based on the above, the TSM was designed to be a 1/10-scale model. Literature review identified scale models that range from 1/5 to 1/12 scale. Optimal values for the scaled test facilities are in the 1/7-to-1/10 range.

TSM features a planar motion capability with programmable trajectory. In a nutshell, it is giant X-Y table mounted vertically (Figure 3). In addition to the simulation of linear (vertical) trajectory, any parabolic (similar to Shuttle) or other generic profile can be incorporated in the test sequence. This was deemed necessary to support the liftoff sequence of Delta, Titan, Atlas, and any other U.S. rockets. TSM will permit the simulation (increase or decrease) of liftoff rates and handle any drift during the ascent stages of the rocket as the tower is cleared. TSM can also handle nozzle tilt requirements. Besides providing the capability to operate remotely from over 200 meters, care was taken to minimize flat reflecting surfaces and include weather protection features for outdoor use.

CONCLUSIONS

A test capability to simulate rocket launch trajectories and to generate nonstationary, scaled acoustic loads is presented. TSM, for the first time, will enable researchers to study the dynamic effects of acoustic loads accurately and help them to assess the vibration responses generated by the launch of rockets on pad equipment and structures. Impact of launch-induced acoustic noise and its influence on the design of ground support equipment is vital to mission success. Immediate LST research will focus on reducing acoustic environments at the payload, vehicle, and ground systems, to develop new launch exhaust management systems. LST therefore represents a leap in technological innovation in the area of vibroacoustic research and development, hitherto not available to architects, engineers and designers of rocket launch systems.

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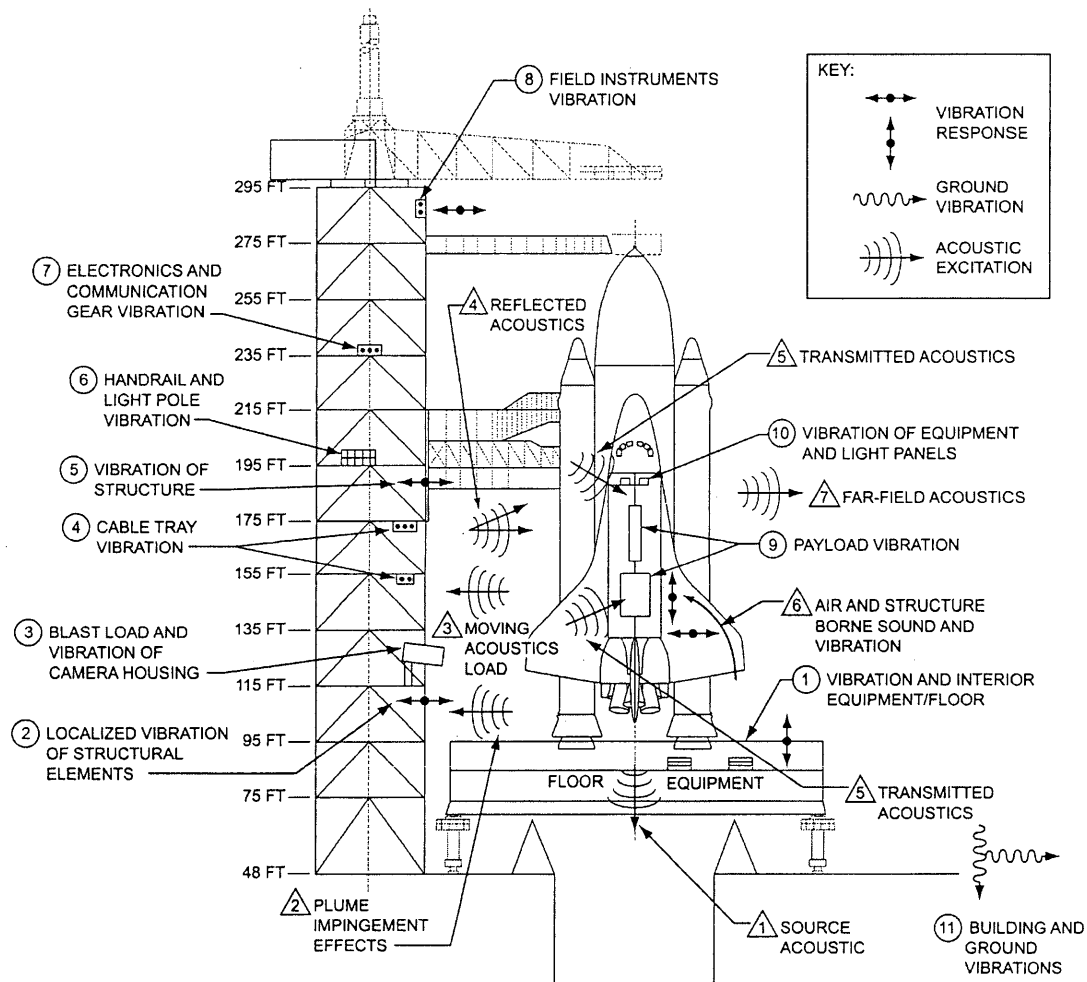
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Table 1. TSM General Features

Feature	Qualification
Minimum Lifecycle	Operable for minimum of 10 years
Minimum Usage Rate	Up to 1500 times per year; 5 to 6 launches per day
Payload Weight	200 pounds (lb)(90.72 kilograms [kg]); rocket and flex lines
Exhaust Duct Envelope	10 feet high \times 10 feet wide \times 30 feet long
Launch Structure Envelope	10 feet high \times 30 feet wide \times 30 feet long
Flex, instrumentation, and photography lines	To be able to traverse in vertical and horizontal directions freely
Remote Control Operation	Operable from a distance in excess of 700 feet
Transportable	Ability to disassemble and move to a different location
Adjustable Tilt Axis	Mount rocket nozzles up to 10 degrees from vertical axis
Reflecting Surfaces	Minimize flat and reflecting surfaces for acoustics
Weather Protection	Weatherproof paint and material selection in design
Lightening Protection	Consideration due to location of TSM
Malfunction Protection	Multiple redundant safety features built in for fail-safe operation

Table 2. TSM Performance Parameters

Parameter	Quantification
Rocket Vertical Thrust	5 to 100 lbs.(2.27 kg to 45.36 kg)
Rocket Vertical Motion	30 ft maximum (9.14 m) and selectable
Rocket Horizontal Motion	12 ft maximum (3.66 m) and selectable
Rocket Vertical Speed	0-5 ft/s in 0.1 ft/s increments (0.61 m/s in 0.031 m/s)
Rocket Horizontal Speed	0 to 2 ft/s in 0.1 ft/s increments (0.24 m/s in 0.031 m/s)
Programmable Trajectory Motion	Planar motion with programmable trajectory option (linear, parabolic, or any generic profile)

**Figure 1. Effects of Acoustics on Pad Structures**

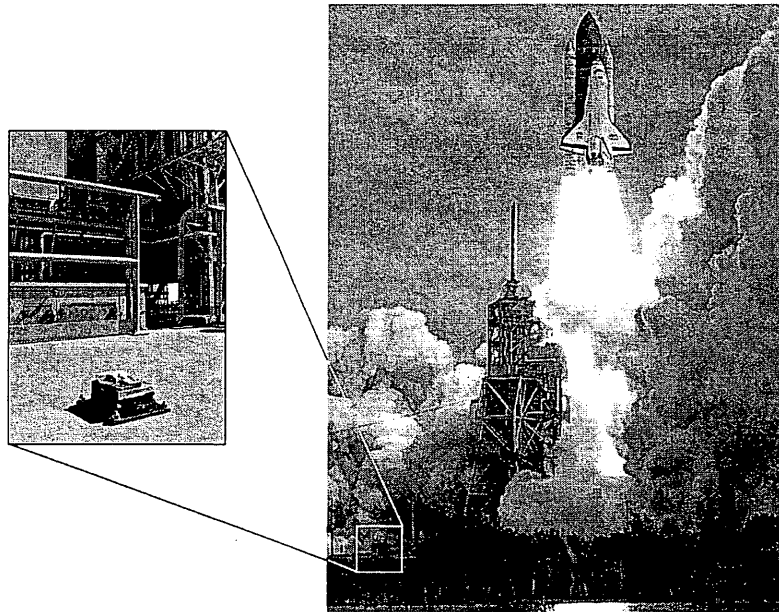


Figure 2. Verification Test Article

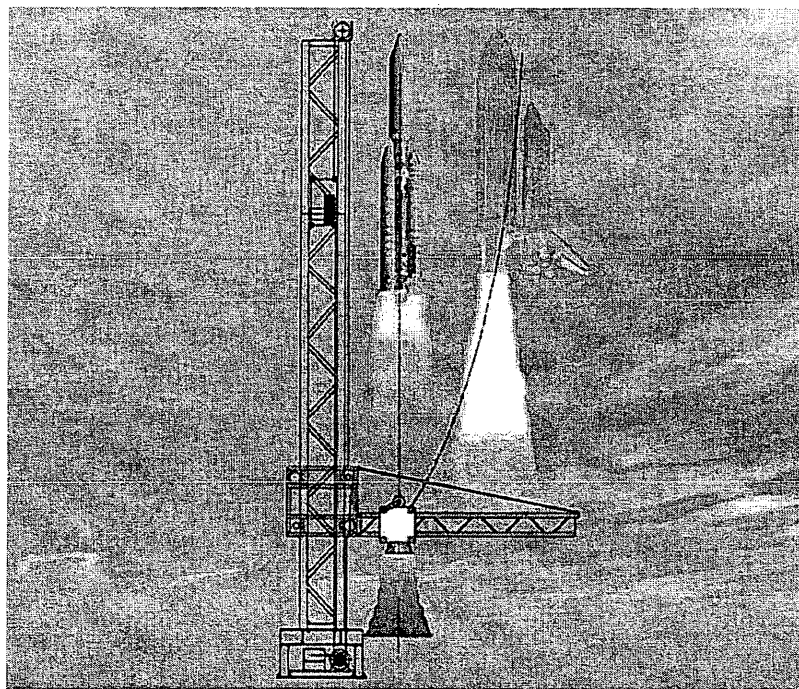


Figure 3. Trajectory Simulation Mechanism